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TECHNOLOGY ASSESSMENT OF HIGH PULSE ENERGY CO_2 LASERS FOR REMOTE SENSING FROM SATELLITES

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Abstract

Recent developments and needs for research are reviewed for extending the lifetime and optimizing the configuration of CO_2 laser systems for satellite based remote sensing of atmospheric wind velocities and trace gases.

CO_2 laser systems for operational satellite application will require lifetimes exceeding one year. Recent progress in the development of efficient low temperature catalysts and gas mixture modifications for extending the lifetime of high pulse energy closed cycle common and rare isotope CO_2 lasers and of sealed CW CO_2 lasers is reviewed. Future research needs including diagnostic tests are discussed.

Pulsed satellite CO_2 laser systems with heterodyne detection for atmospheric measurements require operation at approximately 10 Joules and 10 pulses per second with single axial and transverse mode output. Accurate Doppler lidar wind velocity measurements require narrow bandwidth low frequency chirp pulses with durations greater than one microsecond; accurate Differential Absorption Lidar trace gas measurements benefit from shorter pulses. Several CO_2 laser configurations are currently under development to meet these requirements including: unstable resonators, master oscillator power amplifiers and telescopic stable resonators, using UV or E-beam preionization. Progress in these systems is reviewed and tradeoffs in the system parameters are discussed.

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Technology Assessment of High Pulse Energy CO_2 Lasers for Remote Sensing from Satellites

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Introduction

Since the technology assessments of a Global Wind Measurement Satellite (WINDSAT) System in the 1981 Lockheed Report (ref. 1) in the 1983 Astro Report (ref. 2) and a 1983 SPIE paper by NASA LaRC (ref. 3) considerable progress has been made toward the development of CO_2 lasers with required pulse energies of 10 Joules at 2 to 10 pulses per second, 3 to 5μsec pulse durations, and frequency stability needed for accurate Doppler lidar wind velocity measurements. New approaches for extending CO_2 laser lifetimes to satellite applications also are under investigation. High pulse energy CO_2 lasers with shorter pulse durations $\geq$ 0.1μsec are applicable to Differential Absorption Lidar for water vapor and trace gas measurements [e.g., NOAA (ref. 4), LaRC (ref. 5) M.I.T. Lincoln Laboratories (ref. 6), JPL (ref. 7), and GSFC (ref. 8)]. CW CO_2 lasers are applicable to total column DIAL trace gas measurements with ground reflection [e.g., JPL (ref. 9) and LaRC (ref. 10)], and also play a vital role as low power auxiliary lasers for high pulse energy lidar, as local oscillators for heterodyne detection, and as injection control for stable high pulse energy laser operation. The

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application of low power modulated CW laser and low pulse energy long lifetime CO_2 lasers to space station rendezvous and proximity operation was discussed by LaRC at a recent workshop (ref. 11).

One of the reasons for considerable progress in high pulse energy lasers is that four different CO_2 laser approaches with long pulses and low frequency chirp for Doppler Lidar are in the advanced stages of development at NOAA, Air Force Geophysics Lab., the British Royal Signal and Radar Establishment and NASA LaRC. Under a contract with Spectra Technology, Inc., (formerly Mathematical Sciences NW), NOAA has developed a UV preionized unstable resonator CO_2 laser with projected ≈2 Joule/pulse output (ref. 12). The Air Force Geophysics Laboratory is developing an E-beam sustained unstable resonator laser with ≈1 Joule/pulse (ref. 13), based on a previous contract with General Electric Company. Recently, the British RSRE has demonstrated a 1 Joule/pulse E-beam sustained laser with a stable telescopic resonator. (ref. 14). Under a contract with CLS Laser Systems Inc., LaRC is developing a Master Oscillator Power Amplifier with ≈1 Joule/pulse (ref. 15). This new MOPA system uses a pulsed master oscillator and power amplifier, to satisfy the strict long pulse and frequency chirp requirements for high pulse energy Doppler lidar. The MSFC MOPA system (ref. 16) which has been used for Doppler lidar wind velocity measurements from the CV990 is a quasi-CW amplitude modulated MOPA with pulse energies ≈20mJoule. A high pulse energy CO_2 lidar system is also under development by the Naval Surface Weapons Center (ref. 17). The rapid progress in high pulse energy stable CO_2 lasers also owes a considerable debt to the British Royal Radar Establishment (ref. 14) for contributions

in reducing the frequency chirp due to laser induced medium perturbations (LIMP). A comprehensive evaluation of external injection control for single mode operation of high pulse energy lasers by JPL (ref. 18) and initial studies by Javan on an LaRC grant (ref. 19) also contributed to this progress.

Another aspect of the rapid progress is that new techniques for long lifetime space applications of high pulse energy common and rare isotope closed cycle CO_2 lasers are being studied in-house at NASA/LaRC (refs. 20, 11); new results, including rare isotope $C^{18}O_2$ operation are given later. Rare isotope operation is needed for improved atmospheric transmission and can yield an increase in the aerosol scattering coefficient due to enhanced scattering at $\approx 9.1\mu m$. Lifetime extension of low power sealed CW CO_2 lasers is being studied at NASA GSFC in a combined in-house and contractual program with the University of Maryland (ref. 21). Important contributions in extending the lifetime of low pulse energy CO_2 lasers are also being made at the British RSRE (ref. 22). Lifetime extension of thyratrons through magnetic pulse compression to satisfy the need for fast rise time switching of electric discharge circuits is an important development [JPL (ref. 23) and Spectra Technology Inc. (ref. 24)]. Long lifetime closed cycle CO_2 lasers also are crucial for tactical and space based DOD systems and other applications such as isotope separation and commercial welding, where the large gas supplies needed for open cycle/flow through operation become overly expensive.

The technology assessment is presented in two sections. In the first section the latest developments for extending the lifetime of high pulse energy and CW CO_2 lasers are evaluated, since long lifetime for satellite based operations is one of the key remaining problems for CO_2 lasers in

space. The next section concerns different approaches for high pulse energy CO_2 laser development involving a UV preionized Master Oscillator Power Amplifier at LaRC; a UV preionized unstable resonator at NOAA; an E-beam sustained unstable resonators at AFGL; and an E-beam sustained telescopic stable resonator at RSRE.

Long Lifetime Common and Rare Isotope CO_2 Lasers

The electrons in electric discharge CO_2 lasers cause dissociation of CO_2 into O_2 and CO and attach themselves to electronegative molecules such as O_2, forming negative O_2 ions, and yield generally larger negative ion clusters by collisions with CO or other molecules (ref. 25). For closed cycle, sealed CO_2 laser operation the concentration of negative ions/clusters may become sufficiently high to form discharge instabilities (refs. 26, 27) which may ultimately disrupt the CO_2 laser operation. The decrease in CO_2 concentration due to dissociation into CO and O_2 will reduce the average repetitively pulsed or CW laser power, even if no disruptive negative ion instabilities occur. In order to maintain CO_2 concentration and reduce negative ion formation, the recombination rates of CO and O_2 must be increased, or the dissociation reduced. In essence, there are two techniques to accomplish these goals. One involves modification of the CO_2:N_2:He laser mixture to increase the recombination and modification of the electric discharge behavior to reduce the dissociation. The other involves solid state catalysts with sufficiently high recombination rates at temperatures which are not excessive which may be attained by heating from the laser medium or other means of using the dissipative non-lasing power. For low pressure CW lasers sputtering may also disrupt the laser operation which may, however, be reduced by R-F excitation (ref. 21).

One of the important cases for modification of the laser mixture involves additions of small concentrations of CO. The trend toward increased recombination rates can be explained in terms of a steady state equilibrium process approached in CW or repetitively pulsed CO_2 lasers. For an equilibrium CO_2 dissociation/recombination process

$$2\ CO_2 \rightarrow 2\ CO + O_2$$

the O_2 concentration, given by

$$[O_2] = \frac{K\ [CO_2]^2}{[CO]^2},$$

where K the equilibrium constant,

is strongly reduced by the addition of CO with resulting increase in CO_2 formation. Addition of H_2 will also reduce the O_2 concentration, however, at the expense of potentially undesirable H_2O formation.

The corona discharge (refs. 28, 29) provides a potential means for reduction of the dissociation products through discharge modification, because of the short delay between the preionizing and main discharges, which tends to minimize the buildup of negative ions and of photo-dissociated products during the UV preionization stage. The uniformity of the discharge also offers an advantage. The preionization with the corona discharge may not be as high as with spark arrangements, and the lifetime of the dielectric structure used in corona preionization requires some further investigation. The pulsed unstable resonator developed by NOAA through contract with Spectra Technology Inc. (ref. 2) uses a corona preionized discharge. Note that E-beam sustained lasers operate at lower E/N

values, where E is the electric field and N the total particle density, than UV preionized discharges, with resulting tendencies for reduced dissociation. Reduction in pressure of the laser medium can make the discharge more tolerant to formation of negative ion clusters from the CO_2 dissociation products, because of reduced collisions at lower pressures; the larger negative ion clusters should have more severe effect on discharge instability formation than the negative O_2 ions. Reduction in negative ion formation due to diffusion to the walls occurs only at very low pressures not generally used in CW CO_2 lasers.

The advantage of solid catalysts is that they can provide higher CO/O_2 recombination rates than gas additions with resulting lower average power reduction and higher efficiency of closed cycle sealed repetitively pulsed or CW lasers. High temperature ($\geq$300°) catalysts such as Pt and Pd alone or on some substrate, such as Al_2O_3 (ref. 30), have been frequently used to achieve high recombination rates. The purpose of the substrate is to increase the catalyst surface and offer support. The necessity for external heating to high temperatures reduces the total system's efficiency for space based operation, and is also undesirable for commercial and DOD applications. To obtain operation at lower temperatures catalysts are chosen which participate in the recombination process by effectively reducing the catalyst work function through interaction of the dissociation product, CO, with the catalyst (reduction), and concurrent replacement through the other dissociation product O_2 (oxidation). These two steps permit the catalysts to act like a true catalyst which maintains its structure during the catalytic recombination process. One of these catalysts used for several years is Hopcalite, a combination of copper and

managanese oxide, CuO and MnO, and other oxides (refs. 31, 32). A Hopcalite catalyst is also used in the 200mJ/pulse, up to 150 p.p.s. CO_2 laser developed by LSI Laser Science Inc. The interaction of the catalyst oxides with the dissociation products CO and O_2 essentially occurs through reaction of the oxygen in the catalyst with CO, forming CO_2, and replenishment of the oxygen lost from the catalyst with the dissociation product O_2. An improved version of the Hopcalite catalyst was proposed and evaluated by LaRC (ref. 20) by using a combination of Cu and CuO. For this catalyst the oxygen from CuO reacts with the dissociation product CO to form CO_2 ultimately forming Cu through the step of cuprous oxide Cu_2O, while the dissociation product O_2 reacts with Cu in the catalyst, forming CuO. The catalyst structure Cu/CuO is thus maintained. Improved operation was obtained by using a $Cu/Cu_2O/CuO$ catalyst.

A more recent catalyst developed by RSRE (ref. 22) and LaRC (Ref. 20) is Pt/SnO_2 or Pd/SnO_2, where the combined action of Pt or Pd on SnO_2 and interaction with the dissociation products permits operation at considerably lower temperatures than Pt or Pd alone or on an Al_2O_3 substrate, and which appears to offer improvements over Hopcalite and $Cu/Cu_2O/CuO$ catalysts. Experimental demonstration of the efficiency of this catalyst has been given by RSRE for a ≈30mJoule/pulse 100 p.p.s. CO_2 lasers (ref. 22) and by LaRC for a 1 Joule/pulse, 20 p.p.s. Lumonics 820 TEA CO_2 laser (ref. 20). At LaRC, furthermore, a surrogate catalyst facility, described in the experimental section, is used to study the effectiveness of these catalysts as a function of temperature for common isotope $C^{16}O_2$ and rare isotope CO_2 laser operation, with special emphasis on $C^{18}O_2$; recall that $C^{18}O_2$ provides improved atmospheric transmission and has the potential of

yielding an enhanced aerosol scattering coefficient at ≈9.1μm. Rare isotope $C^{18}O_2$ laser operation has been demonstrated with a Pt catalyst on Al_2O_3 substrate at temperatures $\geq$300°C at Los Alamos National Laboratory (ref. 30); although Al_2O_3 was regarded as a substrate and not a participant in the catalytic process, special care was required to reduce the exchange or scrambling of the oxygen in $Al_2{}^{16}O_3$ with the dissociation products $^{18}O_2$ and $C^{18}O$ of the laser medium. Experiments described in the next section give preliminary indication that rare isotope $^{18}O_2$ and $C^{18}O$ exchange with $Pt/Sn^{16}O_2$ may be inhibited at considerably lower temperatures than for Pt on Al_2O_3 substrate.

Finally note, that although the use of Pt/SnO_2 catalysts is very promising for common and rare isotope operation, the use of small gas concentration additions, such as $C^{16}O$ or $C^{18}O$ also needs to be studied, although the recombination rates are lower, and large additions of CO would somewhat reduce the laser efficiency because of less efficient vibrational transfer from CO to CO_2, than from N_2 to CO_2.

Studies at LaRC of Solid Catalysts and CO Addition

The solid catalyst studies at LaRC are performed in two facilities, one a closed cycle CO_2 laser, where CO addition studies are also performed and, two, a surrogate facility using laser gas mixtures. The two facilities are described in detail in ref. 20.

A schematic of the closed cycle CO_2 laser facility is shown in Figure 1. The closed cycle laser tests were performed with a Lumonics model TEA laser specially constructed to be leak free operating as an unstable resonator at ≈0.7 Joule/pulse and 10 p.p.s.

Concentration of dissociation products was monitored with a gas chromato-

graph. The laser mixture was circulated over an external catalyst heated to temperatures between 100° and 270°C. Catalyst samples were placed in ≈2" i.d. by 4" long quartz tube.

The catalysts tested were $Cu/Cu_2O/CuO$ and Pt/SnO_2. Representative results are given here for Pt/SnO_2. The test results with $Cu/Cu_2O/CuO$ using a smaller catalyst surface area than Pt/SnO_2 are given in Ref. 20; tests will be repeated with equal catalyst surface area. Results of the tests with Pt/SnO_2 are shown in Figure 1 where average laser power, catalyst temperature, and mole percent of the dissociation products CO and O_2 are plotted against time in hours. At catalyst temperatures of 200°C the laser experienced a drop from initial average power of 6.7W at 10 p.p.s. to a steady state average power of 6.2W, which is 93% of initial power. Even at a catalyst temperature of ≈100°C, ≈90% average power is available. The CO and O_2 concentrations vary as expected with temperature, i.e., for the lower temperatures their concentration is high; the catalyst surface area was not optimized in these tests. The tests were performed in excess of 5 hours or in excess of 1.8×10^5 pulses at 10 p.p.s. Long term tests with a well defined catalyst surface area are in the planning stage. Note, the Lumonics laser was sent to the contractor, CLS Laser Systems Inc., for conversion to a power amplifier, and a replacement laser for catalyst studies has now become available.

Experimental studies of the recombination of common isotopes $C^{16}O$ and $^{16}O_2$ and rare isotopes $C^{18}O$ and $^{18}O_2$ have been performed in a surrogate reactor facility which is shown schematically in figure 3. In the surrogate facility catalyst samples were placed in a 0.4" i.d. by 12" long quartz tube, which fits into a furnace for heating up to ≈350°C. Surrogate laser

mixtures containing small concentrations of CO and O_2 were passed through the catalyst with and without added CO_2. The CO and O_2 concentrations before and after recombination on the catalyst were monitored with a gas chromatograph and/or a mass spectrometer; the latter was used especially for rare isotope operation. In one series of tests a stoichiometric mixture of 1.0% CO and 0.50% O_2 was flowed through ≈1g Pt/SnO_2 catalyst samples at flow rates of 5, 10, and 20 std. cm^3/min at room temperature as well as at 55°C, 75°C, and 100°C. The observed conversion efficiency increased with increasing temperature and decreasing flow rate. At a reactor temperature of 100°C essentially complete conversion (100%, within experimental error) was achieved at both 5 and 10 std. cm^3/min. Detailed results of these experiments including their implication for scaling a catalytic reactor for use with the Lumonics laser will be presented in a forthcoming NASA TM.

Most of the research in the surrogate catalyst facility was performed with low concentration ($\leq$ 1%) of CO and O_2 in He at 1atm. and no CO_2 other than that which was formed by the reaction of these two species. Additional tests were performed to determine if the presence of higher concentrations of CO_2 such as would be found in a CO_2 laser would have any effect on the performance of the Pt/SnO_2 catalyst. In these tests the conversion efficiency of the catalyst was measured for each of the following two gas mixtures: (1) a stoichiometric mixture of 1.0% CO and 0.50% O_2 (with 2.0% Ne as an inert internal standard for gas chromatographic analysis) in He at 1atm.; (2) an identical mixture with 16% CO_2 added. Each of these gas mixtures was flowed through a fresh sample (0.120g) of Pt/SnO_2 at 100°C at a flow rate of 5.0 std. cm^3/min for an exposure time in excess of 1000

minutes. The small sample size was chosen to avoid complete conversion of the CO and O_2 to CO_2, as occurred at 100°C with 1g samples, and, thus, to allow any differences which might exist in the conversion efficiencies for the two gas mixtures to be observed.

The results are presented in figure 4 which presents plots of the conversion efficiency of both CO and O_2 for each gas mixture. It can be seen that, for each gas mixture, the conversion efficiency approaches a steady-state value ≈70% after about 200 minutes. It can also be seen that the conversion efficiencies are approximately the same for the two gas mixtures. Thus, omission of CO_2 from the initial test gas mixtures has little, if any, effect. This is important because, for most tests performed in the surrogate catalyst facility, it is desirable to use gas mixtures with no initial CO_2 concentrations in order to accurately measure the small quantities of CO_2 formed by $CO-O_2$ recombination.

For use of rare isotope CO_2 laser mixtures, the possibility of rare isotope interchange with catalysts such as Pt/SnO_2 and Pt/Al_2O_3 containing common isotope oxides must be evaluated. For example, surrogate studies at LaRC have shown that if $C^{18}O$ and $^{18}O_2$ are exposed to a $Pt/Sn^{16}O_2$ catalyst the three possible CO_2 isotopes $C^{18}O_2$, $C^{16}O_2$, and $C^{16}O^{18}O$ are all formed in some quantity. The conversion to $C^{18}O_2$, the desired species, was found to increase with increasing temperature but some formation of isotopes containing ^{16}O occurred at all temperatures studied.

Since maintenance of isotopic integrity of the laser medium is essential, some method of preventing isotopic interchange or scrambling between gases and catalyst material has been sought. One desirable approach, if the nature of the exchange mechanism permits, would be the replacement of

the common-isotope oxygen atoms at the catalyst surface with the rare isotope to be employed in the gas. This would be considerably more economical than replacing all oxygen atoms in the catalyst material with the rare isotope.

Surface isotope replacement was successfully accomplished recently in a preliminary test performed at this laboratory. A sample of 0.12g of $Pt/Sn^{16}O_2$ was heated to 300°C in flowing Ne (flow rate: 5.2 std. cm^3/min). The sample was then chemically reduced in flowing H_2 for 5 minutes and ^{16}O removal (as $H_2{}^{16}O$) was monitored with a mass spectrometer. The sample was then reoxidized with 3% $^{18}O_2$ in Ne for 50 minutes. To assess the effectiveness of the ^{18}O treatment, the sample was cooled to 100°C in flowing Ne and then exposed to a stoichiometric mixture of 2% $C^{18}O$ and 1% $^{18}O_2$ in Ne for 15 minutes. The product CO_2 was monitored with a mass spectrometer. The observed isotopic purity ($[C^{18}O_2]/[CO_2]$total) of the product CO_2 equaled the isotopic purity of the $C^{18}O$ in the reactant gas mixture. Thus, the treatment of the surface was deemed effective, at least for short-term usage. Long-term tests to determine whether or not isotopic migration to or from the bulk of the $Sn^{16}O_2$ occurs at the lower temperatures of 100°C are planned. Note that for the operation of Pt on the intended passive substrate Al_2O_3 (ref. 28) temperatures of $\geq$300°C were required with specially provided wide distribution of Pt on a thin washcoat of Al_2O_3 on stainless steel and unity mass ratio of Al_2O_3 and Pt.

The possibility of CO additions to provide long lifetime closed cycle CO_2 laser operation is also under investigation. In 1983, tests were performed with the Lumonics CO_2 laser with CO concentration additions, varying from 1.5% to 6%. A steady state average power of ≈80% of the initial power

was approached in a somewhat erratic fashion after a brief initial drop for a CO concentration ≈6%. This reduction in average power is considerably higher than for the solid catalyst Pt/SnO_2 at ≈100°C, even without optimization of the catalyst size and design (Figure 3). Preliminary results by Lumonics Inc., (personal communication) for CO additions indicate less reduction in average power at ≈1.5% CO addition. Since the original CO addition experiments were performed with a Lumonics laser which had been in operation for some time (sent to CLS Laser Systems Inc., for conversion to a MOPA), they will be repeated with the clean replacement laser for catalyst studies. The laser will also be operated with rare isotope $C^{18}O_2$ mixtures with $C^{18}O$ addition.

Sealed CW Low Pressure CO_2 Laser Operations

As previously stated, CW low pressure lasers are important as auxiliary lasers for high pulse energy CO_2 lidar, as local oscillators for heterodyne detection, and as lasers for injection control of high pulse energy lasers, as well as for differential absorption lidar with ground reflection.

The key effort in long lifetime studies of sealed CW low pressure CO_2 lasers for space based operation has been performed at NASA/GSFC in a combined in-house and contractual program with University of Maryland. RF excited 2 to 3 watt sealed ≈120 torr CO_2 waveguide lasers have been operated for $>10^4$ hours (ref. 21). Figure 5 is an example of laser power vs time. The initial power reduction to steady state is comparatively small, but after ≈4 x 10^3 hours, a considerable drop to ≈70% power occurs. The RF excitation was produced with one internal electrode (Pt/Cu) and an external capacitively coupled Au/In electrode (Figure 6). A compact waveguide laser with external RF excitation using axially displaced steel or Pt electrodes

is being developed by GSFC and the University of Maryland (Figure 7). Demonstration of a DC excited sealed CO_2 waveguide laser with 2.7×10^3 hour operation at ≈80% initial power (Figure 8) was given by Laughman (ref. 33). In this laser special precautions were taken to shield the laser mirrors from sputtering. However, in RF excited lasers the sputtering should be much less severe.

A large number of CW sealed CO_2 lasers are commercially available under commercial or contractor development for civilian and DOD applications. Some of these lasers show long lifetime (including shelflife), however, with considerable steady state power reduction which may be acceptable for some applications but not yet for space based applications and are not reviewed here. In some commercial lasers, the extension of CW sealed CO_2 laser lifetimes has also become company proprietary.

Discussion with Dr. Hochuli from University of Maryland, contractor to NASA/GSFC, Dr. Tulip from the University of Alberta, Canada, and other investigators, indicates that one of the major needs for long lifetime sealed CW CO_2 lasers is the development and use of improved diagnostics and the optimization of RF excitation efficiency. Techniques for improved diagnostics are basically available but need to be properly funded, although they may not appear to be the most exciting development. For example, one diagnostic technique would be the provision of minute leaks from sealed lasers for mass spectrometer measurements of the products. Another technique which offers the possibility of internal gas concentration diagnostics during CO_2 laser operation involves tunable diode laser spectroscopy at different wavelengths providing non-excessive absorption along the laser length. Improved analysis of internal laser surfaces is also important.

High Pulse Energy CO_2 Laser Systems

Optimum Master Oscillator Power Amplifier Operation

A detailed discussion of the Master Oscillator Power Amplifier and a comparison with the unstable resonator for high pulse energy CO_2 lidar applications is given in the 1983 NASA LaRC technology assessment (ref. 3) with emphasis on Doppler lidar. Important insights for high pulse energy MOPA development are also given for the example of Nd:YAG Doppler lidar by Stanford University (ref. 34).

The main advantage of a Master Oscillator Power Amplifier is that the frequency chirp and the pulse duration and shape can be primarily controlled at the lower pulse energies of the master oscillator. The frequency chirp is negligible in the power amplifier, essentially because it is not a resonant system. Some distortion and reduction in pulse duration may occur in the power amplifier because the leading portion of the pulse causes the release of some of the stored energy and decreases the population inversion, leaving less energy for the trailing portion to extract. For a rectangular pulse, for example, the pulse undergoes a sharpening of the leading edge and a reduction in pulse halfwidth. This distortion can be corrected in two basic ways. One involves pre-distortion of the master oscillator pulse shape through electro-optical modulation which compensates for the predictable distortion in the saturated region of the power amplifier. Such pre-distortion has been discussed as an option for the high pulse energy CO_2 MOPA Doppler lidar at LaRC (ref. 3, Appendix) and for the Nd:YAG MOPA Doppler lidar under development at Stanford University.

Another way for correcting the pulse distortion in the power amplifier is possible for the CO_2 laser with CO_2:N_2:He mixtures where the long storage of energy in N_2 can be gradually released to the lasing CO_2 medium with resulting increase in pulse duration.

The conditions for efficient energy extraction from the Master Oscillator Power Amplifier are now discussed (see also ref. 3 for CO_2 lasers and ref. 34 for Nd:YAG lasers). For power amplifier media with inclusion of relaxation rates, the pulse amplification equation is

$$\frac{dE}{dx} = g_o E_s \left(1-e^{-E/E_s}\right). \tag{1}$$

When integrated from a given input energy/cm^2, E_{in}, to an output energy/cm^2 E_{out}, with E_s as saturation energy/cm^2, equation (1) yields

$$E_{out} = E_s \ln\left[1+e^{g_o L}\left(e^{E_{in}/E_s} - 1\right)\right] + E_{in} \tag{2}$$

where g_o is gain coefficient and L is gain length.

Efficient energy extraction is obtained in the saturated region where $E_{in}/E_s > 1$ and E_{out} approaches

$$E_{out} = E_s g_o L + E_{in} \tag{3}$$

Note, that $E_{out} = E_s g_o L$ is the upper bound for laser resonators as well as power amplifiers. The saturation energy/cm^2, E_s, varies with the nature of the inversion (2, 3, 4 level) and with the pertinent relaxation rates. The 2 level value of $E_s = h\nu/2\sigma$, with σ the stimulated emission cross-section, has been demonstrated for short CO_2 laser pulses $\approx$2nsec to be $\approx$ 0.150 Joule/cm^2. For longer pulses where $N_2 \rightarrow CO_2$ transfer relaxation rates and repumping can be effective, and for uniform lasing media, E_s approaches 0.5 Joule/cm^2 at $\approx$1atm operation.

UV Preionized MOPA

The 1 Joule/pulse CO_2 MOPA being developed by CLS Laser Systems Inc., on contract to LaRC under an OAST program funded in FY84, uses a newly developed master oscillator and a commercial Lumonics 820 CO_2 TEA laser modified as the power amplifier. The Lumonics laser operates at ≈1 Joule/pulse at 20 p.p.s. It was concluded that the expense of developing a new power amplifier could be avoided since the power amplifier does not control the chirp and can tolerate somewhat higher CO_2 concentrations or total pressures for operation at longer pulses. The modified Lumonics power amplifier has the constraints of a 3cm x 2.3cm cross-section and a gain length of 48cm. In order to obtain ≈1 Joule/pulse output a three pass amplification was chosen. The schematic of the complete three pass MOPA configuration is shown in Figure 9.

Experimental small signal gain measurements taken on-axis and off-axis indicate that the gain across the excited Lumonics amplifier cross-section is very nearly uniform at a gain coefficient, g_o = 3%/cm. Power amplification results have shown that a master oscillator pulse of 40mJ is amplified to 130mJ after single pass and to 420mJ after two passes. These results are within 10% of theoretical values for g_o = 3%/cm and E_s = 0.5 Joule/cm^2. In the first pass the laser beam is not saturated, but becomes saturated in the second and third pass. These initial results were obtained without the use of an intracavity gain cell for mode control in the master oscillator to demonstrate the feasibility of the converted Lumonics power amplifier. Preliminary results of 0.75 Joule output have been obtained for three pass amplification using non-ideal windows. Tests of three pass amplification are in preparation using the master oscillator

with full operation of the intracavity gain cell and stabilizing locking loops.

The master oscillator has a hybrid TEA laser configuration using an intracavity CW laser gain cell operating above threshold for injection controlled single transverse and longitudinal mode output up to 50mJ at 20 p.p.s.; it can be operated up to 100 p.p.s. For operation sufficiently far above threshold, the intracavity gain tube reduces the gain switched spike with some increase in pulse duration. For the longer pulse durations up to 5μsec, the master oscillator is operated at pressures down to 300 torr (see also ref. 2) because at the lower pressures the smaller CO_2 concentration and population inversion permit more gradual stored energy transfer from N_2. Under certain conditions to be discussed later the lower pressure may also reduce the frequency chirp. Experiments/theory for frequency chirp reduction and their application to the MOPA are discussed next.

The frequency chirp in the later pulse stages is based on the laser induced medium perturbation (Limp) theory with thermalization of the vibrational laser energy. According to experimental/theoretical studies can be controlled frequency chirp through changes in laser energy output, cavity length, and laser beam cross-section. The frequency chirp for medium long pulses ≈1 to 3μsec follows the form $\Delta\nu = \alpha t^2$ (refs. 35, 36) and for long 4 to 8μsec pulses with E-beam sustained lasers by the form $\Delta\nu = \beta t^3$, (refs. 37, 14), with some differences between chirpcoefficients α and β. For the present purpose, the main similarity in structure of the chirp coefficients involving laser dimensions and output energy is given. The chirp coefficient α for a gaussian beam distribution is

$$\alpha \propto \frac{\varepsilon_{out}}{(L_{cav})\ (\text{Beam Area})^2} \tag{4}$$

where ε_{out} is the laser output energy and L_{cav} is the cavity length. Thus, the low output energy of the master oscillator is an advantage for reducing the frequency chirp. For higher pulse energies increase in beam area or cavity length, while maintaining proper gaussian beam distribution, is needed for chirp reduction.

Frequency chirp reduction with reduced pressure is outlined by Spectra Technology Inc., (ref. 38) by extending the RSRE model for medium long pulses with $\Delta\nu = \alpha t^2$ dependency. It is concluded that the RSRE model assumptions are satisfactory at pressures $\geq$1atm, but not at 0.5atm or lower. For the lower pressures the gas heating lags behind the laser energy extraction significantly. When the laser gas pressure is decreased from 1 to 0.5atm, keeping all the dimensions and the discharge energy density per atmosphere constant, significant chirp reduction is reported. Reduction in pressure for the present master oscillator will reduce the pulse energy and the frequency chirp. Publication of experimental and theoretical details of the pressure effect on chirp is not yet available (personal communication with Spectra Technology Inc.).

Other proposals for chirp reduction involve frequency modulation inside the resonator by RSRE (ref. 39) or outside the resonator by Javan (ref. 19). Laser chirp reduction has been of interest for many years and several aspects have been evaluated, as shown, e.g., in W. Koechner's text (ref. 40, pp. 234, 235).

The preceeding considerations open up several options for the optimum design of a Master Oscillator Power Amplifier for 10 Joule/pulse output. One approach is to operate the master oscillator at low pulse energy and low chirp with subsequent power amplification over a comparatively large gain length for efficient energy extraction in the saturation region in the later passes. Multi-pass amplification in a short gain cross-section has the advantage of compactness but the multipass beams may not quite cover the entire cross-section; overlapping of the beams has the advantage of more rapid saturated energy extraction, but has the potential problem of beam distortion. A different option of this approach is to have several gain sections with the laser beams covering the entire lasing cross-section. Another approach is to operate the power amplifier with $E_{in} \geq E_s$ for highly efficient energy extraction. The higher pulse energy, low chirp laser recently demonstrated by RSRE (ref. 14) operating with large beam cross-section could satisfy the requirements with some focusing of the beam area to assure $E_{in} \geq E_s$. However, it must be noted that the large cross-section and the longer pulse duration ≈3μsec (with options of 5μsec) was obtained through an E-beam sustained operation at atmospheric pressure. Since it is not certain that E-beam sustained operation is desirable for space operation, and the need for very long pulse durations for Doppler lidar still needs to be evaluated, the full potential of UV preionization at pressures $\leq$ latm for chirp reducton needs to be studied. Use of modulation techniques for chirp reduction (refs. 39, 19) needs to be further investigated; they are of special interest for low pulse energies, as in the master oscillator for MOPA operation, to avoid damage to the modulator at higher pulse energies or repetition rates.

UV Preionized Unstable Resonator

A UV corona preionized unstable resonator CO_2 laser has been under development by NOAA and has been recently delivered by Spectra Technology Inc. (formerly MSNW). This device operating at 2 Joule/pulse at a repetition rate of 50 p.p.s. with a frequency chirp <200KHz (ref. 12) and pulse durations from 1 to 5μsec is primarily oriented toward ground based Doppler lidar and aerosol scattering cross-section measurements. A conceptual design has also been developed for a free flyer satellite operating at 10 Joule/pulse and 2 p.p.s. (ref. 2). One of the main reasons stated for the choice of UV corona instead of previously suggested E-beam sustained operation (which presently may have problems in lifetime and radiation shielding) is that the physical nature of the frequency chirp has been clarified by RSRE (ref. 14) and UV preionized discharges are fully able to meet the requirements. In addition, it is stated that the pulse duration requirements have been reduced from 7μsec to 3 to 4μsec. Operation with pulse durations of 1 to 5μsec for the ground based device will further evaluate this contention. Some characteristics of unstable resonators with UV corona preionization are discussed in greater detail.

The advantage of unstable resonators is that they provide high pulse energy operation by operating in a large volume laser medium in a configuration that provides single transverse mode and primarily reflective optics. However, the unstable resonator far field pattern may not be fully useful for heterodyne detection (ref. 3). This is exemplified for the simple case of a positive branch confocal unstable resonator in Figure 10. The output coupling for the NOAA unstable resonator occurs conveniently sideways, using a tilted scraper mirror inside the cavity, Figure 11, but

the fundamental relations are similar. The fractional single pass geometric output coupling in Figure 10 is approximately $(1-1/M^2)$ where $M = a_2/a_1$ is the magnification factor between the mirrors. The near field pattern will have a central main lobe surrounded by concentric diffraction rings or side lobes. For small output coupling, corresponding to M near unity, the far field pattern will contain a large amount of energy in the side lobes rather than the main lobe. The fractional energy in the central lobe vs. geometrical output coupling is given in figure 10. For the NOAA unstable resonator CO_2 laser the energy in the central lobe is ≈50%, using a Spectra Technology Inc. unstable resonator design which somewhat improves the simplified relations for geometrical output coupling (personal communications). The backscattered energy in the side lobes can be used for direct detection but is generally wasted for heterodyne detection; thus, ≈50% of the output energy is utilized for heterodyne detection. Note that for the MOPA, or a stable resonator using a limiting circular aperture output coupler, the Airy pattern would yield ≈84% of the output energy for heterodyne detection and larger values if the beam underfills the aperture with somewhat reduced energy utilization.

In order to provide the large output coupling for a large output energy fraction in the central lobe beneficial for heterodyne detection, the single pass gain g_oL needs to be comparatively large; g_o is the gain coefficient and L is the gain length. The NOAA UV corona preionized unstable resonator CO_2 laser operates at reduced pressures of ≈300 torr to provide longer pulse duration through reduction of CO_2 partial pressures (ref. 2). The reduced pressure is required in order to maintain a constant gain at reduced CO_2 partial pressure since gain is proportional to σn_i,

where σ is inversely proportional to total pressure and n_i the population inversion density is proportional to CO_2 partial pressure. However, the output energy will decrease with reduced total pressure and n_i. The energy input will also decrease, thus the wall plug efficiency may remain reasonably high.

The benefits of large beam cross-section and reduced pressure on reduction in the frequency chirp are discussed in the previous section for the case of a gaussian beam from an unstable resonator. A brief discussion of the effect of unstable resonator mode structure on the frequency chirp is given in the conference proceedings by Spectra Technology Inc. (ref. 38), but the results have not yet been published. Measurements of the frequency chirp in the NOAA unstable resonator are in progress (personal communications from R. Lawrence).

The NOAA unstable resonator uses external injection control for single longitudinal mode operation. Intracavity injection locking for stable resonators used in master oscillators for a MOPA by LaRC, or for a stable telescopic resonator by RSRE, reduces the need for locking loops between the laser used for injection control and the ≈1 Joule/pulse laser and permits greater reduction of the gain switched spike. The comparative total systems efficiencies need to be evaluated.

E-Beam Sustained Unstable Resonator

The Air Force Geophysics Laboratory is developing an E-beam sustained high pulse energy unstable resonator CO_2 laser for ground based Doppler lidar measurements from a mobile van (ref. 13). The pulse energy varies from 0.2 to 1.0 Joule at a pulse duration from 1.0 to 5.0μsec, and the chirp is <200KHz. The device has been modified from a larger laboratory

device, designed and demonstrated by Jacobs et al., from General Electric Company (ref. 41) to fit into a mobile van. The Jacobs' device has been operated at energies up to several Joule/pulse with a chirp ≈200KHz; however, at that time accurate chirp measurements were not performed.

One of the unique features of the device is the use of an unstable, confocal positive branch ring cavity/resonator with external injection control. Such a ring cavity, with external injection control, is also used for a low pulse energy 50mJ/pulse stable resonator device operated at LaRC (ref. 42) prior to installment of ≈1 Joule/pulse MOPA. The advantage of the ring cavity is that it facilitates single longitudinal mode operation by reduction of spatial hole burning. The ring laser facilitates injection locking through the output coupler since the injection beam is not colinear with the output beam.

One advantage of E-beam sustained operation is that it provides discharge operation over longer periods for matching pulse durations, >3μsec without lowering of CO_2 concentrations, e.g., by reducing the laser pressure. It thus becomes possible to operate at correspondingly higher CO_2 concentrations and output energies if the longer pulses are required. In addition, E-beam sustained operation permits operations at lower voltages and E/N values with correspondingly higher laser efficiencies. The improved control of pulse duration/shape for E-beam sustained operation avoids long pulse tails, undesirable for CO_2 lidar operation; however, elimination of pulse tails with plasma switches has been successfully demonstrated (ref. 43). E-beam sustained operation does not offer advantages for reducing the main chirp effect in the later pulse stages due to laser induced medium perturbation. The potential disadvantages of E-beam

sustained operation involving lifetimes of the E-beam injection foils and X-ray shielding have been extensively documented.

E-Beam Sustained Telescopic Stable Resonator

Recently, 1Joule/pulse operation has been demonstrated with an E-beam sustained stable resonator with 3μsec long pulse duration and ≈50KHz frequency chirp by RSRE (ref. 14). In order to obtain a large beam cross-section for reduction in frequency chirp the stable resonator was operated with a telescope; a hybrid gain cell provides injection for single longitudinal mode operation, while the telescopic magnification maintains a single transverse mode.

It is stated in the discussion of ref. 14 that "the only problem encountered in the device was optical damage to intracavity components; obviously those in the contracted beam experience the highest intensities and are thus susceptible to damage". Possible use of other than intracavity injection (e.g., external injection control) are suggested. Better suppression of the gain switched spike could also be effective, but would require operation sufficiently far above threshold with high intracavity intensities.

Concluding Remarks

Tradeoffs studies of unstable and stable resonator high pulse energy operations for long pulse Doppler lidar need to be performed for E-beam sustained and UV corona preionized operation at atmospheric and lower pressures. The stable resonator advantage of more complete use of the output beam distribution for heterodyne detection than the unstable resonator must be weighed against it's potentially higher energy density with increased

damage to optical components. Of potential interest is the use of a properly designed stable resonator with frequency chirp control as master oscillator in a high pulse energy MOPA device with the master oscillator operating at reduced pulse energy, but sufficient energy/cm^2 to provide efficient MOPA operation with low frequency chirp. The comparative long term alignment stability of stable and unstable resonators and Master Oscillator Power Amplifiers for the strict stability requirements of Doppler lidar should be evaluated.

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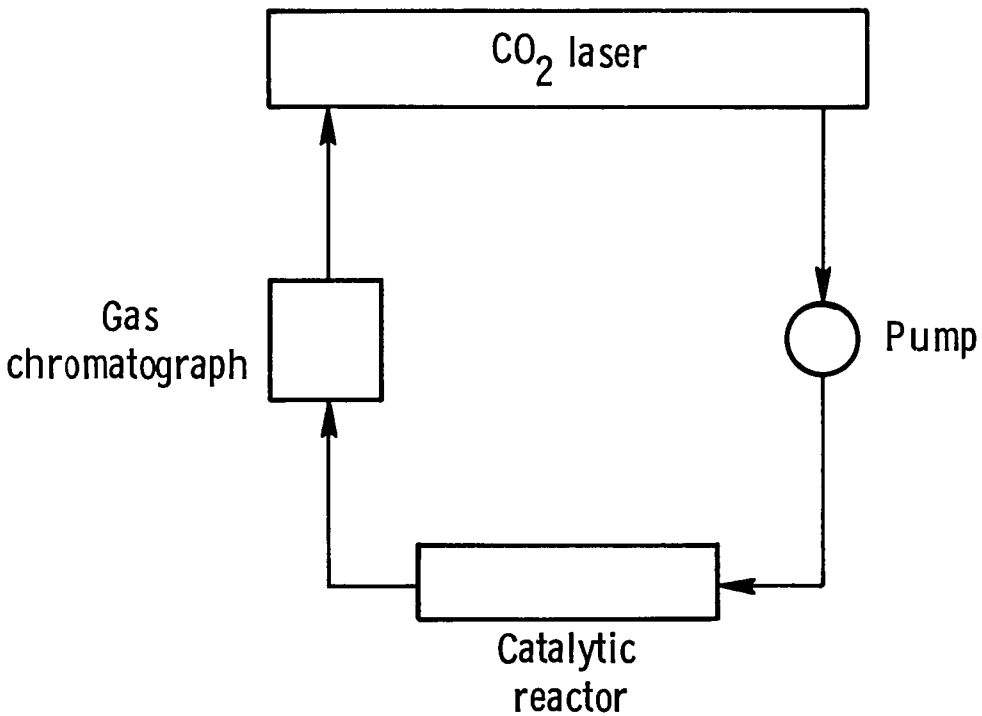


FIGURE 1. SCHEMATIC DIAGRAM OF GAS RECIRCULATING SYSTEM FOR CLOSED CYCLE LASER OPERATION

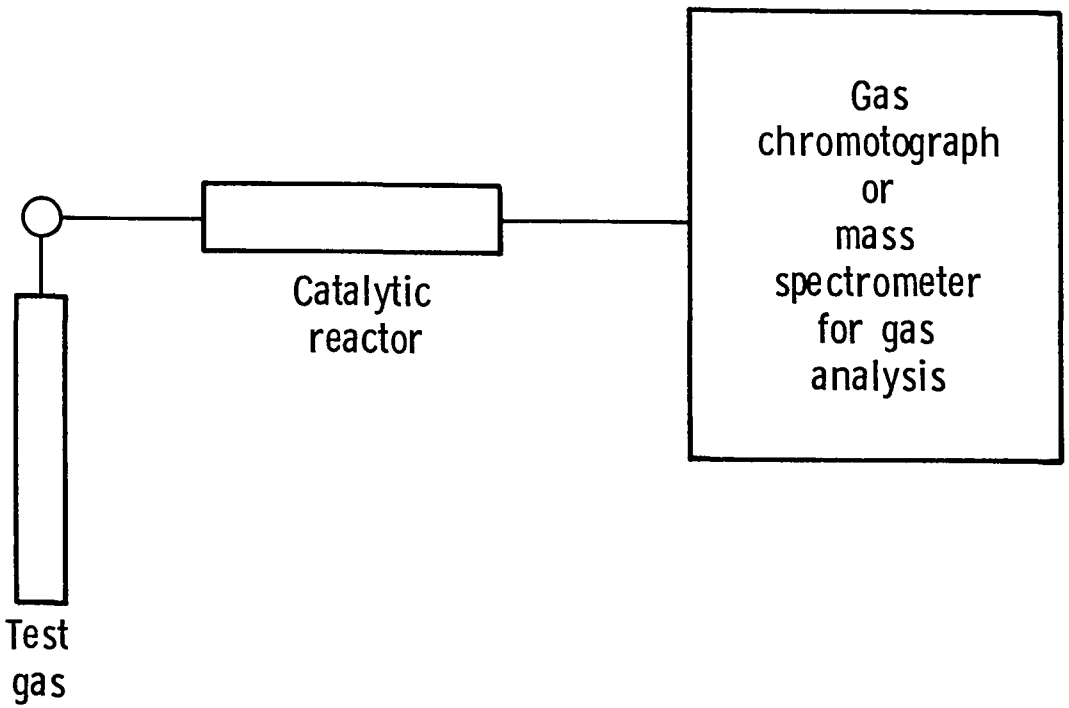


FIGURE 2. SCHEMATIC DIAGRAM OF APPARATUS FOR TESTING CATALYSTS WITH SURROGATE GAS MIXTURES

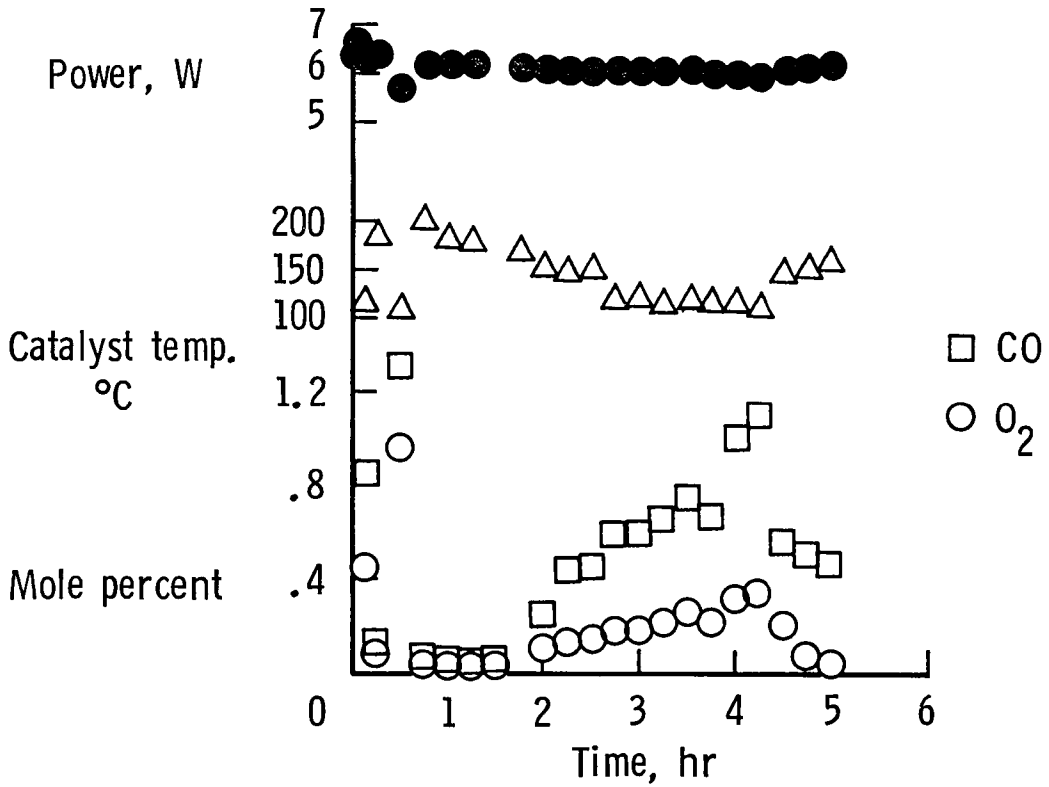


FIGURE 3. LIFETIME STUDIES FOR CLOSED CYCLE OPERATION OF CO_2 LASER AT 10 P.P.S. USING PLATINUM ON TIN OXIDE CATALYST

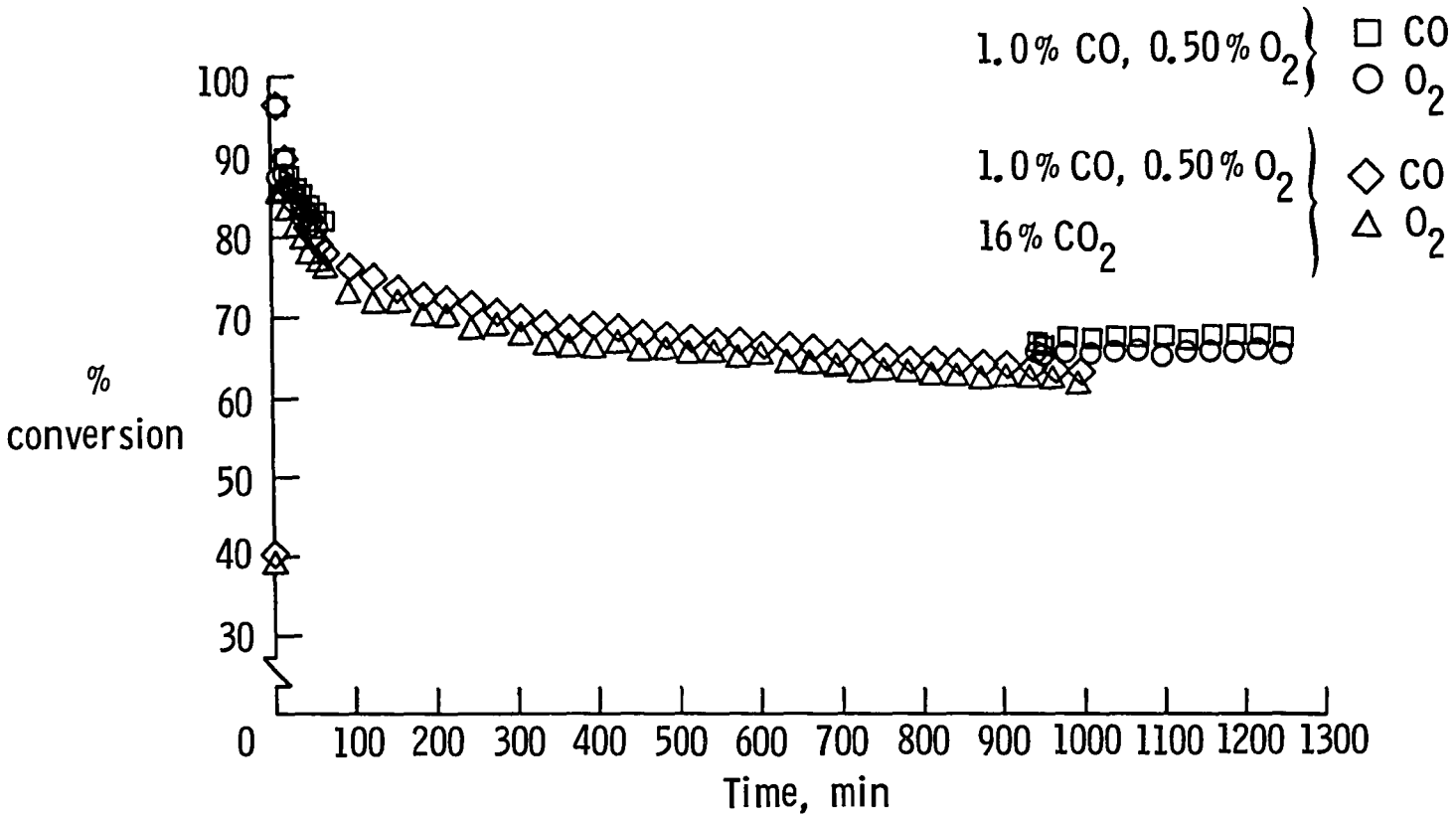
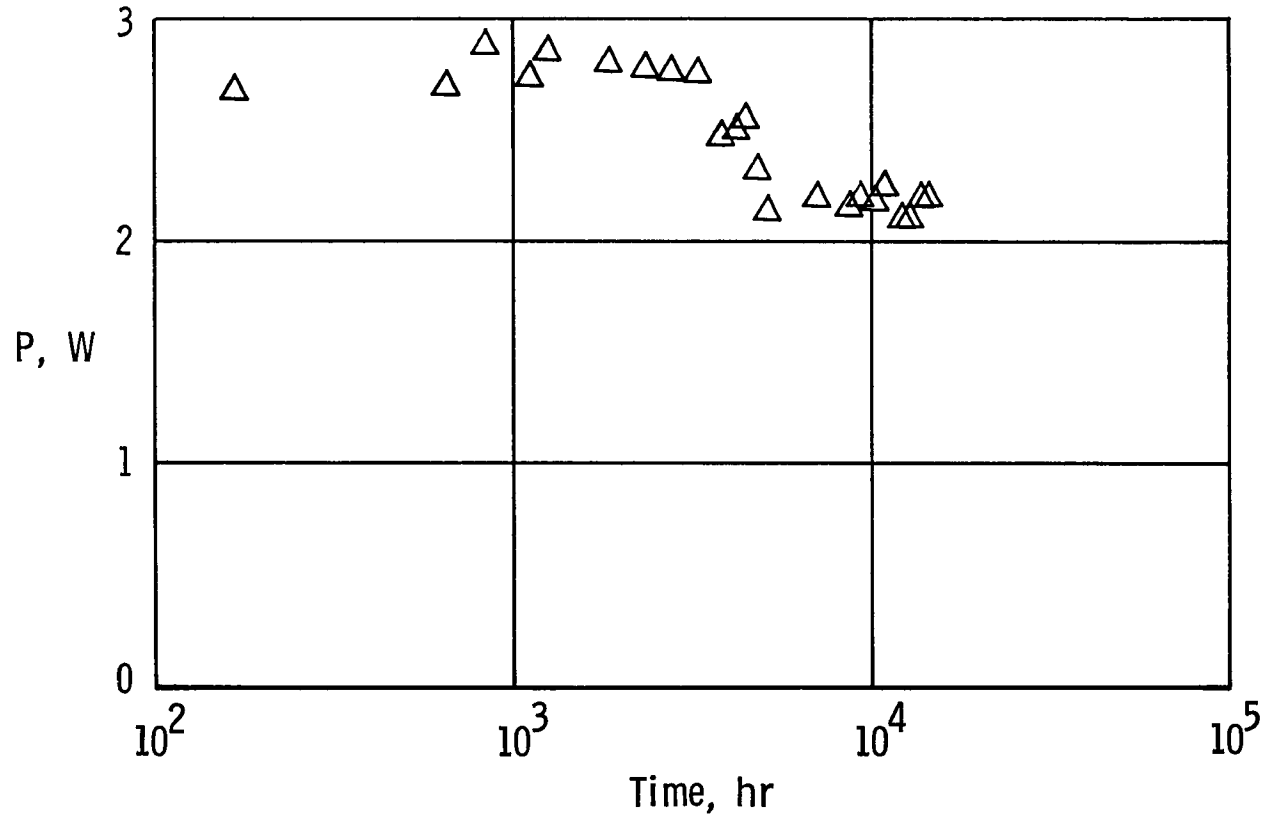


FIGURE 4. CONVERSION EFFICIENCY OF CO AND O_2 TO CO_2 FOR A 100C Pt/SnO_2 CATALYST VS TIME



Hochuli, U. E., 1984

FIGURE 5. LIFETIME STUDY OF RF-CW CO_2 WAVEGUIDE LASER

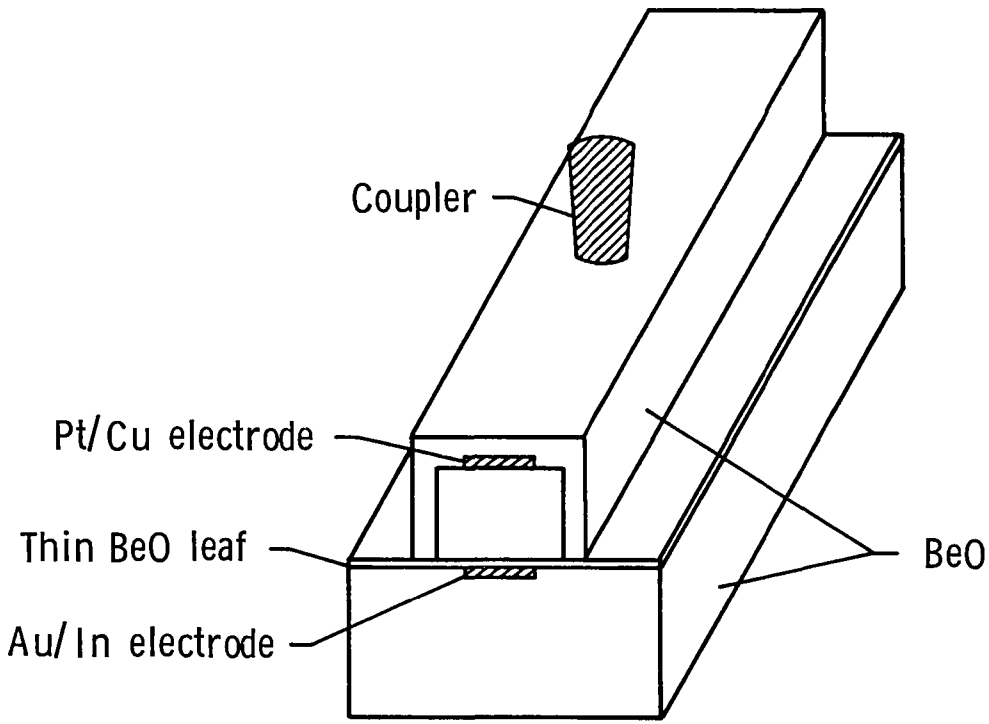


FIGURE 6. CHANNEL STRUCTURE RF EXCITED CO_2 WAVEGUIDE LASER

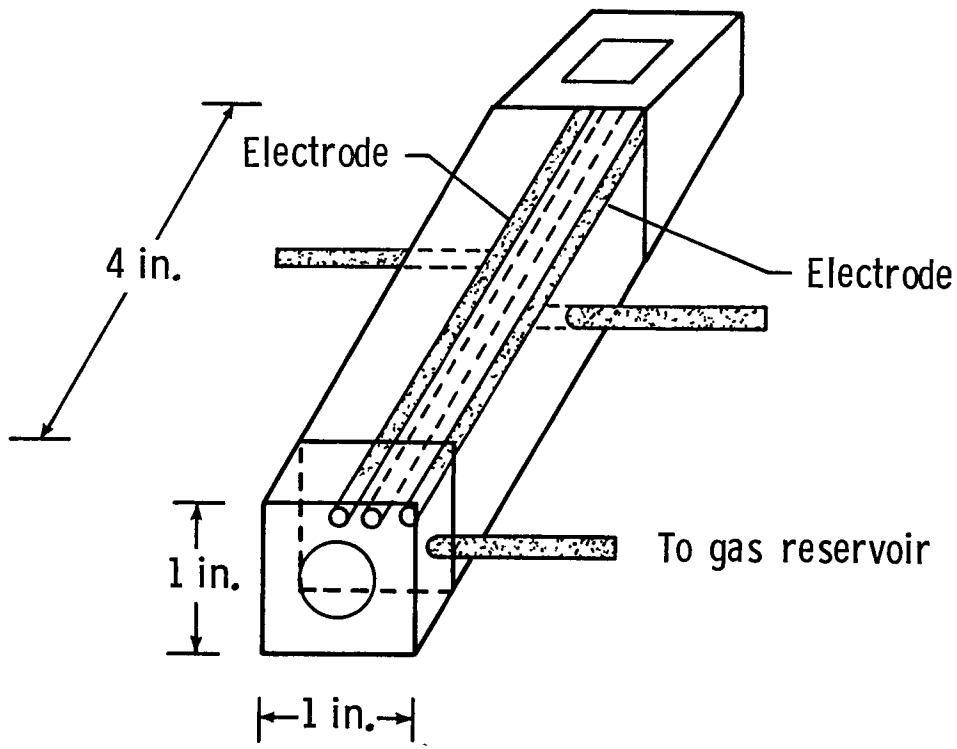


FIGURE 7. INTEGRATED STRUCTURE RF EXCITED CO_2 WAVEGUIDE LASER

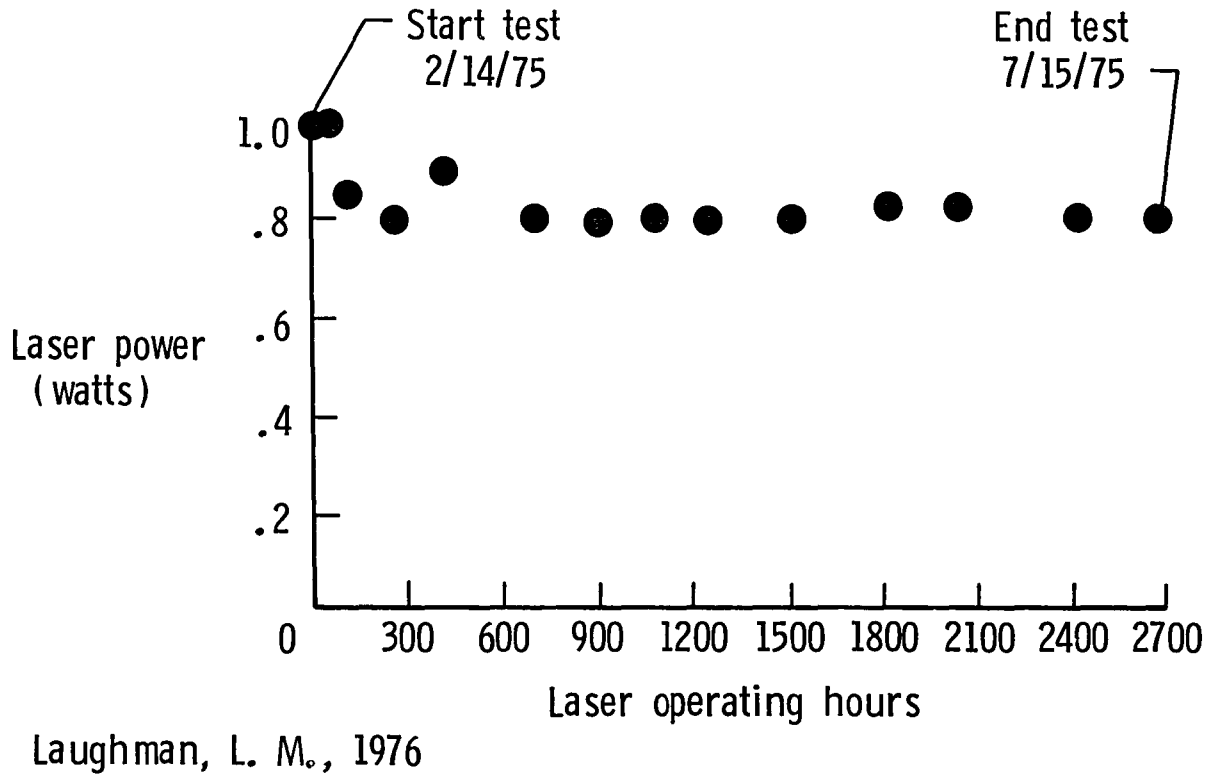


FIGURE 8. LIFETIME STUDY OF DC-CW CO_2 WAVEGUIDE LASER

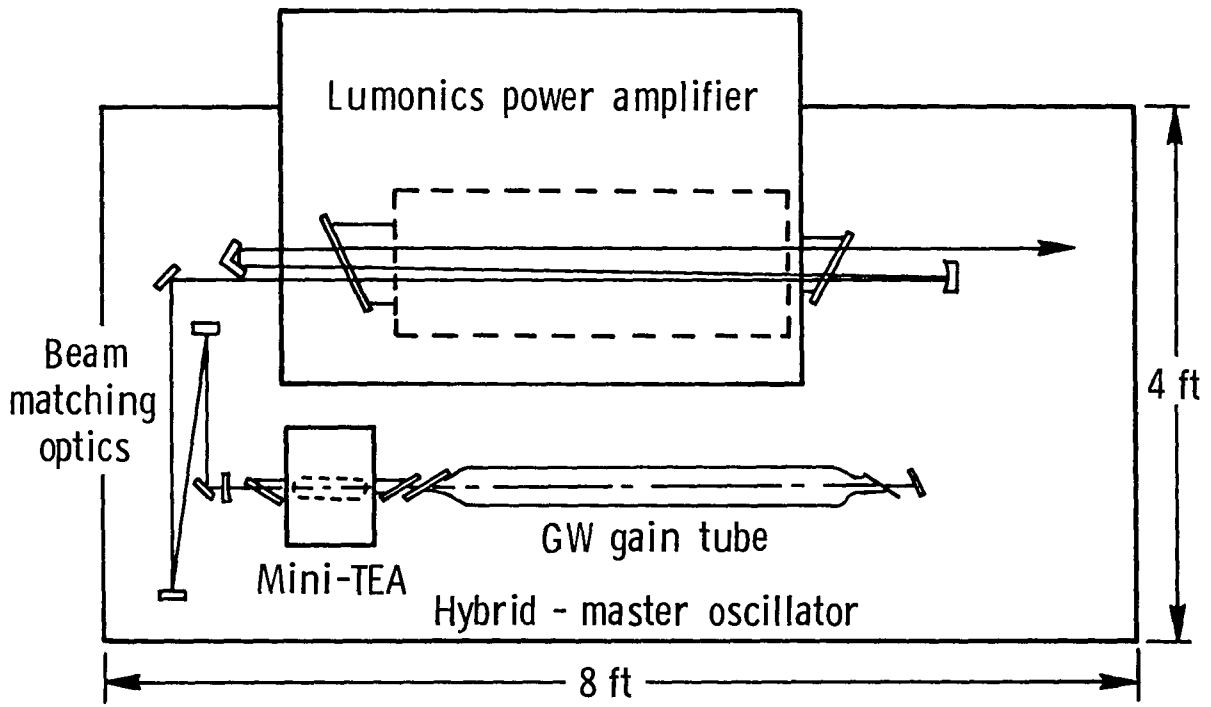
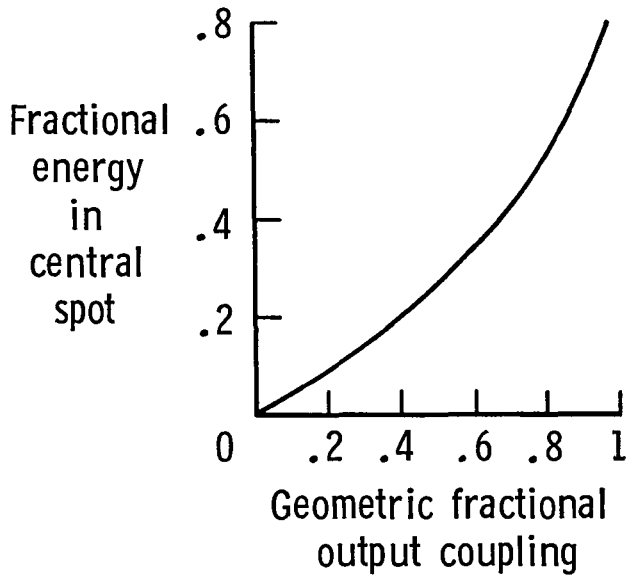
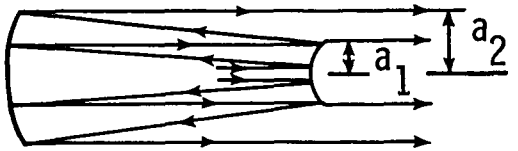


FIGURE 9. MASTER OSCILLATOR POWER AMPLIFIER - THREE PASS CONFIGURATION





Positive branch confocal unstable resonator

Geometric fractional output coupling =

$$\frac{a_2^2 - a_1^2}{a_2^2}$$

FIGURE 10. UNSTABLE RESONATOR RELATIONSHIPS

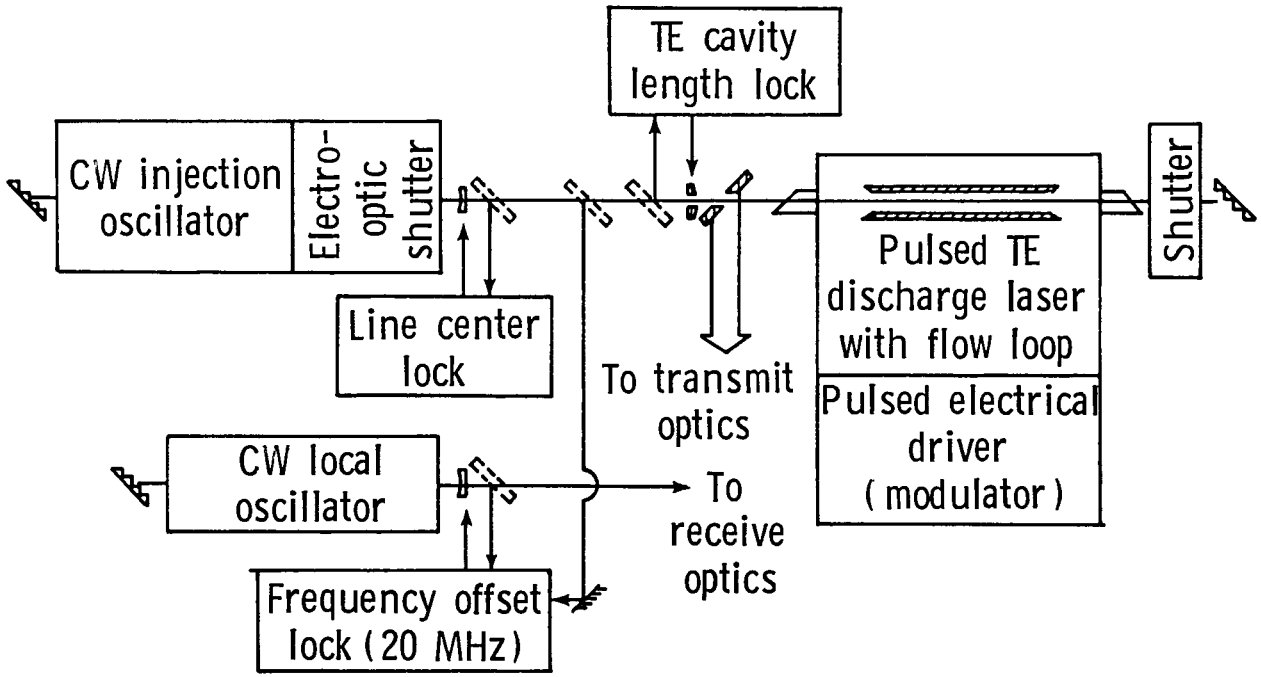


FIGURE 11. CONCEPTUAL DESIGN FOR HIGH AVERAGE POWER LIDAR

1 Report No	2 Government Accession No	3 Recipient's Catalog No
NASA TM-86415		

4 Title and Subtitle	5 Report Date
Technology Assessment of High Pulse Energy CO_2 Lasers for Remote Sensing from Satellites	April 1985
	6 Performing Organization Code 506-54-23-12
7 Author(s) R. V. Hess, P. Brockman, D. R. Schryer, I. M. Miller, C. H. Bair, B. D. Sidney, G. M. Wood, B. T. Upchurch*, and K. G. Brown**	8 Performing Organization Report No
	10 Work Unit No
9 Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665	11 Contract or Grant No
	13 Type of Report and Period Covered Technical Memorandum
12 Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	14 Sponsoring Agency Code

15 Supplementary Notes

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**K. G. Brown, Old Dominion University, Norfolk, Virginia.

16 Abstract

Recent developments and needs for research are reviewed for extending the lifetime and optimizing the configuration of CO_2 laser systems for satellite based remote sensing of atmospheric wind velocities and trace gases.

CO_2 laser systems for operational satellite application will require lifetimes exceeding one year. Recent progress in the development of efficient low temperature catalysts and gas mixture modifications for extending the lifetime of high pulse energy closed cycle common and rare isotope CO_2 lasers and of sealed CW CO_2 lasers is reviewed. Future research needs including diagnostic tests are discussed.

Pulsed satellite CO_2 laser systems with heterodyne detection for atmospheric measurements require operation at approximately 10 Joules and 10 pulses per second with single axial and transverse mode output. Accurate Doppler lidar wind velocity measurements require narrow bandwidth low frequency chirp pulses with durations greater than one microsecond; accurate Differential Absorption Lidar trace gas measurements benefit from shorter pulses. Several CO_2 laser configurations are currently under development to meet these requirements including: unstable resonators, master oscillator power amplifiers and telescopic stable resonators, using UV or E-beam preionization. Progress in these systems is reviewed and tradeoffs in the system parameters are discussed.

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